

## Gas Stream Temperature Measurements Via Fourier Transform Infrared Spectroscopy

M. Shahnam\*, S.D. Woodruff\*\*, I. Celik\* and R.G. Logan\*\*

\* Mechanical and Aerospace Engineering Department  
West Virginia University, Morgantown, WV 26505

\*\* U.S. Department of Energy, Morgantown Energy Technology Center  
P.O. Box 880, Morgantown, WV 26507-0880

### Abstract

A temperature measuring technique utilizing a Fourier Transform Infrared spectrometer (FT-IR) is reviewed and tested by applying it to a natural gas/air flame and to a hot gas (air) stream. The numerous problems encountered in using this technique are elucidated. Preliminary temperature measurement results based upon the intensity of the absorption spectrum of the  $\nu_3$  band of carbon dioxide is encouraging when compared to the standard thermocouple readings. Temperature measurements at different locations in a flame indicate that accurate temperature values can be obtained if there is sufficiently large amount of carbon dioxide present compared to the background carbon dioxide concentration.

### Introduction

The problems in measuring the temperature and composition of hot, luminous, and particle-laden flows (i.e. inside coal combustors) have received increasing attention lately (Ottesen and Thorne, 1983). Particle temperature can often be measured by two color pyrometry. Gas phase information, however, is difficult to obtain in these dirty environments. FT-IR spectroscopy is a non-intrusive, in situ optical technique which can determine gas phase composition and temperature (Thorne and Ottesen, 1983). This technique does not perturb the chemical or flow characteristics of the combustion processes. Furthermore, the large spectral region sampled using FT-IR spectrometers permits quantitative determination of low molecular weight gases ( $\text{CO}$ ,  $\text{CO}_2$ ,  $\text{H}_2\text{O}$ , etc.) and hydrocarbons, as well as qualitative determination of heavier hydrocarbons. The temperature of the absorbing species can be determined if the individual vibration-rotation transitions of carbon dioxide, carbon monoxide, or low molecular weight hydrocarbons can be resolved. The aim of this study was to further the development of a procedure for measuring the temperature of hot combustion products based upon the individual vibration-rotation transitions of carbon dioxide. This paper reports on the preliminary results obtained from measurements in a natural gas/air laminar flame. Quantitative information such as temperature and concentration can be obtained from the observed absorption intensities. Ottesen and Thorne [1985] indicated that the characteristics of  $\text{CO}$  and  $\text{CO}_2$  vibrational and rotational energy spectra are the most suitable for temperature measurements. They have mostly used  $\text{CO}$  spectra for this purpose. However for coal combustion,  $\text{CO}$  is usually an unstable reactive compound and may not be readily present for detection. Carbon dioxide will always be present in sufficient concentrations

in any coal combustion system. Therefore, a procedure has been developed to calculate the temperature of a natural gas/air diffusion flame based upon the  $\nu_3$  band of  $\text{CO}_2$  absorption spectrum of the combustion products.

### Theory

The flame temperature is obtained by resolving the vibrational-rotational transitions of  $\text{CO}_2$  as pointed out by Herzberg [1939]

$$I = c_1 (J' + J'' + 1) \text{EXP}[-E(J'')/(kT)] \quad (1)$$

where  $I$  = transition intensity,  $c_1$  = a constant dependent on the vibrational transition,  $J'$ ,  $J''$  = principal rotational quantum numbers for the upper and lower states respectively,  $E(J'')$  = energy of the lower state,  $k$  = Boltzmann's constant and  $T$  = absolute temperature. Equation (1) can be rearranged as

$$\ln[I/(J' + J'' + 1)] = C - E(J'')/(kT) \quad (2)$$

Assuming that the peak absorbance,  $H$ , of each transition is proportional to its transition intensity, a plot of  $\ln[H/(J' + J'' + 1)]$  Vs.  $E(J'')$  should give a straight line with a slope equal to  $-1/(kT)$  according to (2). The rotational temperature,  $T$ , can then be obtained by calculating this slope. The energy levels of the lower state,  $E(J)$ , of the  $\nu_3$  band of  $\text{CO}_2$  (i.e.  $00^0_1-00^0_0$ ) were tabulated by Air Force Geophysical Laboratory (AFGL) and are available upon request, Rothman [1989].

### Experimental Setup and Procedure

The experimental apparatus consisted of four major components: the FT-IR spectrometer, transfer optics, the flame source, and an infrared detector. The FT-IR spectrometer was manufactured by Mattson Instruments, Inc. An Infrared beam was produced from the output of the interferometer and sent across the sample to an MCT infrared detector via transfer optics. Temperature measurements were taken in a flame and in a hot gas stream. The flame was created by burning natural gas with air in a bunsen burner, Figure 1. The hot gas stream was produced by heating the air inside a ceramic reactor, Figure 2. The high velocity jet emanating from the 1/8 inch ID nozzle fitted to the end of the reactor constituted the measuring section. The infrared beam traversing the flame or the hot jet measured the absorption spectra of carbon dioxide. Temperature measurements were based upon 100 scans at a resolution of  $0.125 \text{ cm}^{-1}$  of the background and the sample (i.e. flame). More details of the governing equations and procedure can be found in Celik et al. [1990].

### Results and Discussion

Temperature measurements were taken at three different locations of (1) in the diffusion flame, Figure 1, (2) in the premixed flame, Figure 1, and (3) two inches away from the exit of a jet discharging hot air, Figure 2.

#### Location (1)

Figure 3 illustrates the absorption spectrum of the combustion gases in the outer cone of a natural gas/air flame, location (1). The various combustion species are evident based upon their absorption frequencies. Figure 4 shows the absorption spectrum of the  $\nu_3$  R-branch band of  $\text{CO}_2$ . The flame temperature is calculated based upon the intensity of each line,  $H_i$ , in this region. A plot of  $\ln [H_i/(J_i + J_i + 1)]$  Vs.  $E_i$  should yield a straight line whose slope is equal to  $-1/(kT)$  according to equation (2). This plot is shown in Figure 5. Since the slope of the straight line in Figure 5 is equal to  $-9.982\text{E-}04$ , the flame temperature at the point of measurement should be 1441.37 K. A thermocouple reading of 1394.11 K was obtained at the same point in flame. The difference between the thermocouple reading and the FT-IR measured value can be attributed to the interference of the carbon dioxide absorption spectrum of flame by the amount of carbon dioxide already existing in the room (i.e. background). This is evident from comparison of Figures 6 and 7 which are the absorption spectrum of carbon dioxide at the point of measurement with and without the flame. The difference between these two distributions is the population distribution of carbon dioxide in the flame at the point of measurement. The larger this difference, the less interference exists. Since there is a significant population of the  $\nu_3$  vibration in the flame at this point compared to the population at room temperature, the temperature measured via FT-IR is close to the thermocouple measured value.

#### Location (2)

Temperature measurements based upon the  $\nu_3$  band of  $\text{CO}_2$  absorption spectrum in the inner cone of the flame, approximately 10 mm above the surface of the burner Figure 8, resulted in erroneous values, location (2). The slope of the straight line in Figure 9 was  $-1.209\text{E-}03$ , that resulted in a temperature of 1190° K. A thermocouple reading of 589 K was obtained at the same point in the flame. This discrepancy is possibly due to the nonlinear distribution of carbon dioxide in the inner cone of the flame. Figures 10 and 11 illustrate the  $\nu_3$  population distribution of carbon dioxide at the point of measurement with and without the flame. A comparison of the difference between  $\nu_3$  band of  $\text{CO}_2$  in Figures 10 and 11 with Figures 6 and 7, location (1), indicates a smaller distribution in location (2) compared to location (1); i.e. at the wavenumber of 2400.09, this difference is about 12.57 for location (1) and it is about 6.19 for location (2). This seems to indicate that for location (2) there was more interference from the existing amount of carbon dioxide in the room, causing much less accurate temperature readings.

#### Location (3)

Attempts were made to measure the temperature of hot gases in a heated air jet with an exit velocity of approximately 50 m/s, location (3). Figure 12 illustrates the absorption spectrum of carbon dioxide at 2 inches away from the exit of the jet. Carbon dioxide free air was purged through optical access holes on both sides of the jet in order to minimize the pollution of the jet by an external carbon dioxide source. The thermocouple reading was

560 F for this location. However the  $\nu_3$  band of carbon dioxide absorption spectrum was not sufficiently resolved to yield any temperature information. The background and the sample population distributions of the  $\nu_3$  band of carbon dioxide were virtually identical. This meant that there was a significant amount of interference from the carbon dioxide in the room, resulting in wrong temperature values.

### Conclusions

A technique for measuring temperature using FT-IR spectroscopy based upon the  $\nu_3$  band of  $\text{CO}_2$  absorption spectrum was evaluated in a flame and in a heated air jet. Since the intensity of the absorption spectrum of the  $\nu_3$  band of carbon dioxide was the basis for measuring the temperature, any interference of the infrared beam by an outside source (in this case background) seems to cause erroneous results. In the high temperature region of the diffusion flame, there was sufficient population distribution of  $\text{CO}_2$  resulting in an accurate temperature measurement. However, since the population distribution of the  $\nu_3$  band of  $\text{CO}_2$  in the premixed flame region and the hot air stream was comparable to that of the background, inaccurate results were obtained.

### Acknowledgement

Support for this project was provided by Department of Energy, Morgantown Energy Technology Center under contract No. DE-FC21-87M24207, project A.2.

### REFERENCES

Celik, I., Shahnam, M., Katragadda, S., and Usmen, R., "Deposition, Corrosion, Erosion and Sulfur Emission Studies Related to Coal Combustion", Final Report, No.: MAE/90/IC2, Mechanical and Aerospace Engineering Department, West Virginia University, February 1990.

Herzberg, G., "Molecular Spectra and Molecular Structure," V. I, Prentice-Hall, Inc., 1939.

Herzberg, G., and Herzberg, L., "Rotation-Vibration Spectra of Diatomic and Simple Polyatomic Molecules with Long Absorbing Paths," Journal of Optical Society of America, Vol. 43, Number 11, November 1953, pp. 1037-1044.

Mavrodineanu, R., and Boiteux, H., "Flame Spectroscopy," Wiley, 1988.

Rothman, L., Private Communications, 1989.

Ottesen D.K. and Thorne L.R., International Conference on Coal Science, Pittsburgh, PA, p. 621 (August 15-19, 1983).

Ottesen, D.K. and Thorne, L.R., "In Situ Studies of Pulverized Coal Combustion by Fourier Transform Infrared Spectroscopy" International Conference on Coal Science, Sydney, NSW, Australia, p. 351 (Oct. 28-31, 1985).

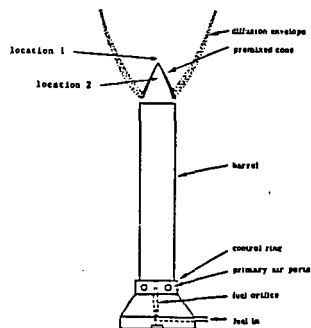


Figure 1 Schematic of a Bunsen Burner.

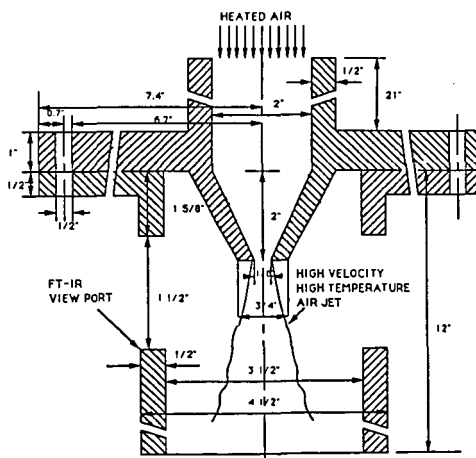


Figure 2 Side View of the Extruded Flow Reactor with the Bunsen.

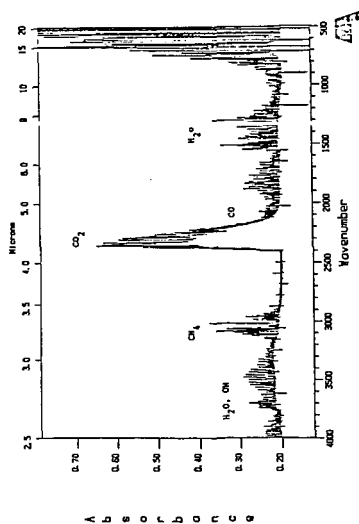


Figure 3 Absorption Spectra of Flame.

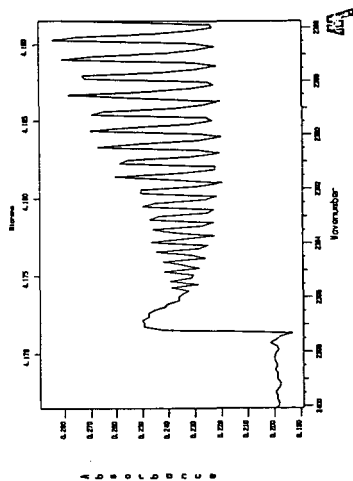


Figure 4 Absorption Spectra of the  $\lambda_3$  Band of  $\text{CO}_2$  (B-branch).

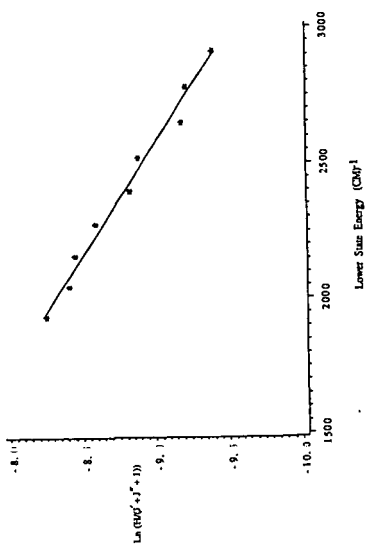


Figure 5 Rotational Temperature of Carbon Dioxide.

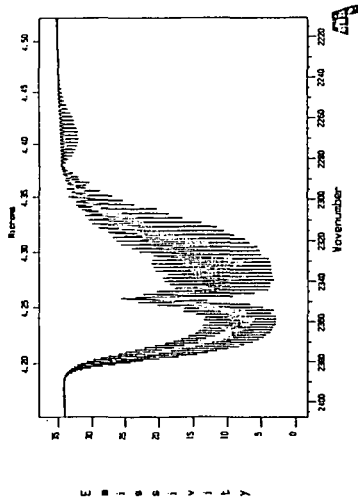


Figure 6 Background Single Beam.

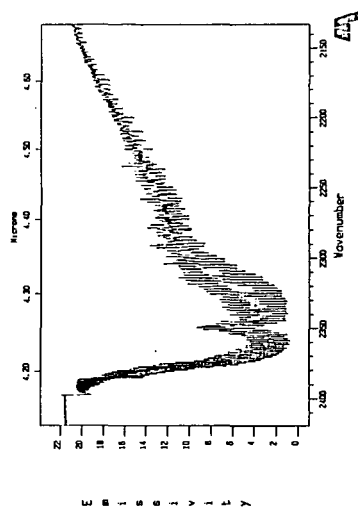


Figure 7 Sample Single Beam.

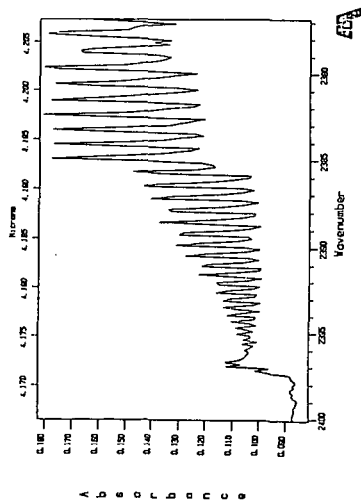


Figure 8 Absorption Spectra of the  $J_2$  band of  $CO_2$  (2-branch).

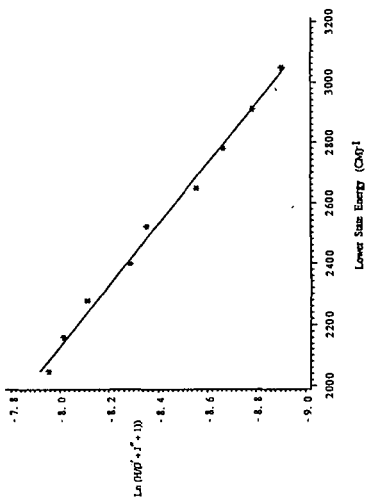


Figure 9 Rotational Temperature of Carbon Dioxide.

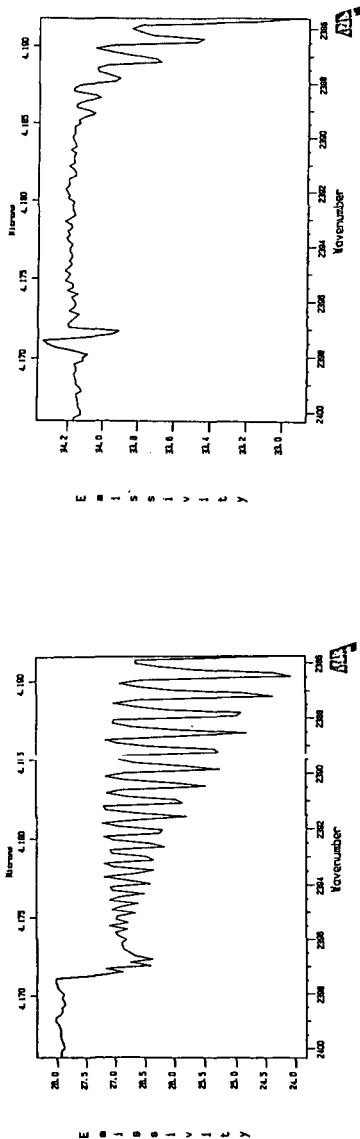


Figure 10 Sample Single Beam.

Figure 11 Background Single Beam.

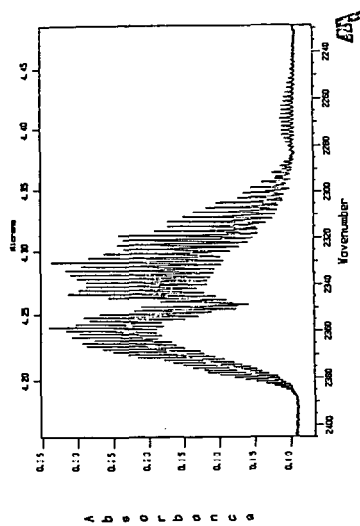
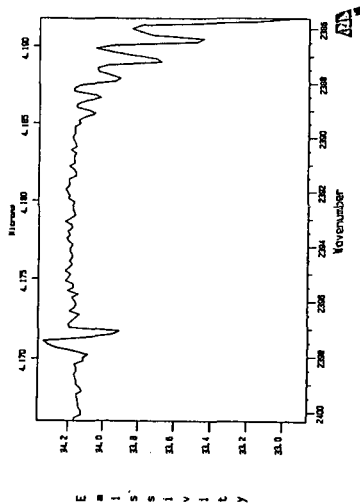


Figure 12 Absorption Spectra of  $\text{CH}_4$  in a Hot Air Jet.